Advanced AEM to address exploration, engineering and environmental challenges

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Summary

The paper and case studies presented will provide examples of how advanced airborne time-domain EM ("TEM") systems can be applied to address challenges in exploration as well as in mine feasibility and infrastructure planning. The case studies will also focus on how the various types of data collected were synthesized to pick likely targets for further follow up.

Characterising depth to bedrock from sparse geotechnical drilling can be risky and the consequences of faulty characterisation can range from frustrating to financially disastrous. With a reliable conductivity contrast, airborne TEM mapping of the subsurface can offer an inexpensive method to reduce uncertainty beyond what geological mapping can do. This approach paid dividends for First Quantum Minerals when mapping the depth of glacial till ahead of finalising site infrastructure in northern Finland. On the strength of the EM model of overburden depth, backed up by subsequent geotechnical boreholes, the infrastructure plan was modified to shift processing equipment from very poor ground to relatively shallow and intact bedrock. The success of the project was based on the availability of petrophysical statistics to tune the EM modelling, and ultimately, on the use of the modelling to guide further drilling to the satisfaction of the engineering team.

In another case, Orca Gold Inc, a Vancouver based company with exploration properties in Africa, determined that their gold project in the Sudan was uneconomic without a reliable source of water. Ground geophysical methods and exploratory boreholes in the immediate area north of the mine indicated that available water contained in a sandstone formation was limited in size and reliability. Construction of a pipeline from the Nile was too expensive, and it was concluded that development of the mine would be economically unfeasible.

Orca decided to employ AEM. Preliminary AEM results from area in the north re-enforced the ground geophysics and borehole results that had indicated water was present but not in quantities sufficient to support mine operations. New targets were identified but were small and did not appear to be economic or were high risk for further exploration. Interpretation of the AEM resistivity data from the west area however identified potential economic zones, and the first boreholes were targeted on the highest conductivity zones. These produced some water but not in usable quantities. Interpretations of the geology were adjusted and the drills were moved to moderate conductivity targets. This approach quickly proved very successful, with a series of boreholes proving high yields of low-salinity water.

Mine infrastructure planning

This TEM survey was carried out for First Quantum Minerals (FQM) in 2010 at the Kevitsa mine site. The Kevitsa mine is located in the northern Finland (see figure 1).

Figure 1: Location of the Kevitsa mine in northern Finland shown with a black star.

In 2008, FQM projected that approximately 1Mt of copper and 750 thousand tons of nickel could be mined at the site. FQM's objective was to find a suitable location for a crusher, which had to be installed on shallow, intact bedrock. Since the overburden needed to be excavated down to the bedrock, FQM was searching for a location with a bedrock depth of less than 10 metres. Geology at the mine is characterized by bedrock overlain by quaternary till, varying in thickness between a few metres up 50 metres. In some areas, the upper part of the bedrock is fractured or weathered, which renders it highly unsuitable for placement of the crusher.

Electrical borehole logs and vertical electrical soundings indicated a generally high electrical conductivity contrast between the quaternary, the weathered/fractured bedrock, and the intact bedrock. A large number of boreholes had been carried out over the years by different contractors. However, the quality of the borehole interpretations varied, and the boreholes were unevenly distributed. Based on this borehole information the original proposed site for the crusher was located in an area with sparse boreholes and a projected overburden thickness of less than 5 metres. Due to sparse borehole information at the selected site, FQM ascribed a significant uncertainty to the depth of the bedrock ("DTB") and decided to commission SkyTEM Surveys to carry out an airborne TEM survey.

A high resolution SkyTEM304 with a dual-moment waveform and 150,000 NIA was employed for the investigation. This system was selected because it offers high near-surface resolution due to its fast turn-off and early useable time gates.

The TEM data was inverted using Aarhus Workbench and 1D laterally constrained multi-layers resistivity models ("MLM"). One disadvantage of MLM is that the model layer interfaces are fixed and logarithmically spaced and independent of the geology interfaces. Hence, for this application it is not possible to determine the DTB directly on the basis of the MLM. Against this backdrop, a statistical approach was employed for estimation of the bedrock depth.

The posterior covariance matrix C_{est} resulting from the 1D-inversions is given by
$C_{est} = [G^T C_{OBS} G + C_m^{-1}]^{-1}$
and was applied to generate 1,000 random resistivity realisations for each layer of each the MLM. These form a probability distribution like the example in figure 2.

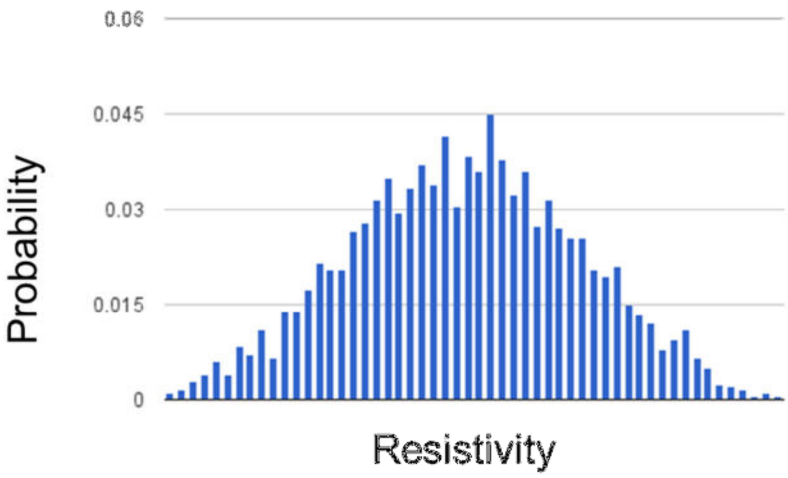

Figure 2: Example of resistivity realisations for one MLM

The probability distribution can be employed to pose statistical questions such as: “what is the likelihood that the layer resistivity is lower than 500 ohm m”.
Based on existing knowledge of the resistivites, the bedrock would be ascribed a resistivity of more than 500 ohm m. The DTB in each TEM sounding location would be determined using the probability distribution. Starting from the top in each MLM:

1. Is the probability of resistivity being lower than 500 ohm m higher than 50%?
2. If 1. is fulfilled then go the next layer.

The DTB is defined as the middle of the first layer in which question 1 above fails.

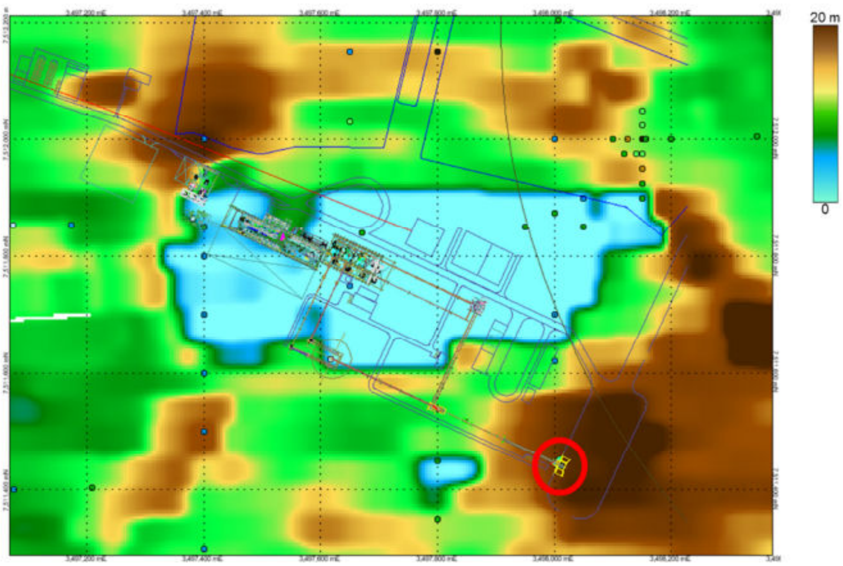

Figure 3: Contour map of DTB estimated on the basis of the TEM data. The original location of the crusher is shown with a red circle.

In the original location of the crusher, the TEM survey indicated that the depth to the bedrock was more than 20 metres and not 5 metres as estimated on the basis of the original boreholes. Against this backdrop, and the significant capital investment, a number of geotechnical drillings were carried out on the basis of the TEM survey. The DTB determined from these boreholes showed a good correlation with the results from the TEM survey as shown in figure 4.

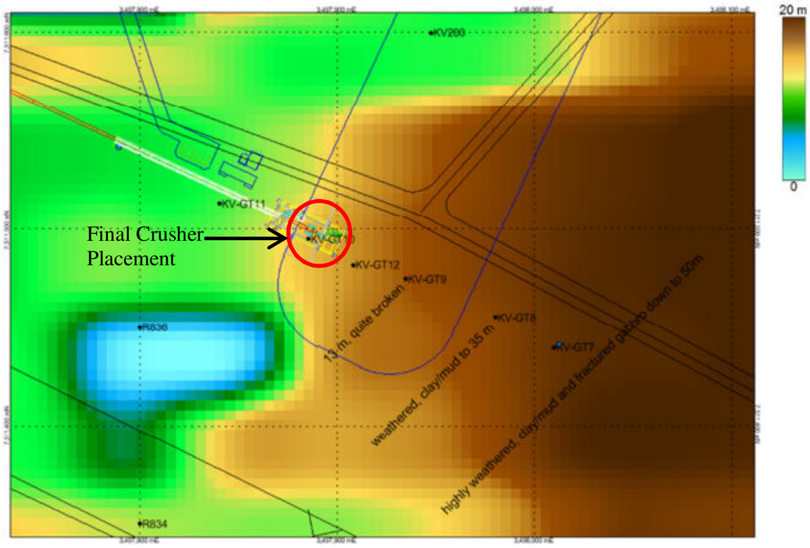

Figure 4: Results of geotechnical drillings (KV-GT*) plotted on top of the TEM generated DTB map.

The normal practice with conventional boreholes was to stop once hard rock is encountered. However, the geotechnical boreholes revealed that the upper part of the bedrock would often be highly fractured or weathered. Conversely, the above-mentioned statistical approach would place the fractured and weathered bedrock in the lower than 500 ohm m category and is the reason for a high correlation between the TEM results and the geotechnical boreholes.

Having reconciled the results from the geotechnical boreholes and the TEM survey, it was decided to place the crusher where the overburden was only 5 metres. Given a reliable conductivity contrast, airborne EM mapping of the subsurface can offer an inexpensive method to reduce uncertainty beyond what geological mapping (logging) can do. The success of this project was based on the availability of petrophysical statistics to tune the EM modelling, and ultimately, on the use of the modelling to guide further drilling. In conclusion, this high resolution TEM survey saved FQM a large sum of money because the original location "would have been disastrous" (Wijns 2016).

Finding water for mine operations

Orca Gold has tenements in the northern Sudan and projected that they could mine 2M oz of gold over a 12 year period. Orca wanted to extend their operations to a new area but was challenged with insufficient water supply. The company had assessed the prospect of building a pipeline to source water from the Nile but deemed it too costly. Existing hydrogeological data suggested it was likely that water could be extracted locally, but the data set was incomplete. Hence, SkyTEM was commissioned to perform an airborne TEM survey to map the groundwater resources and identify locations for pump tests.

The hydrology

The mine site is located on the periphery of the massive Nubian Aquifer System (NAS) that stretches across several countries from northern Sudan to northern Egypt and Libya. In the Dakhla Basin to the north of the survey area, 3-4 km thick sequences of sandstone and siltstone have been deposited overlying the bedrock. However, the mine site is located where the sedimentary deposits are only a few 100 metres thick as shown in figure 5.

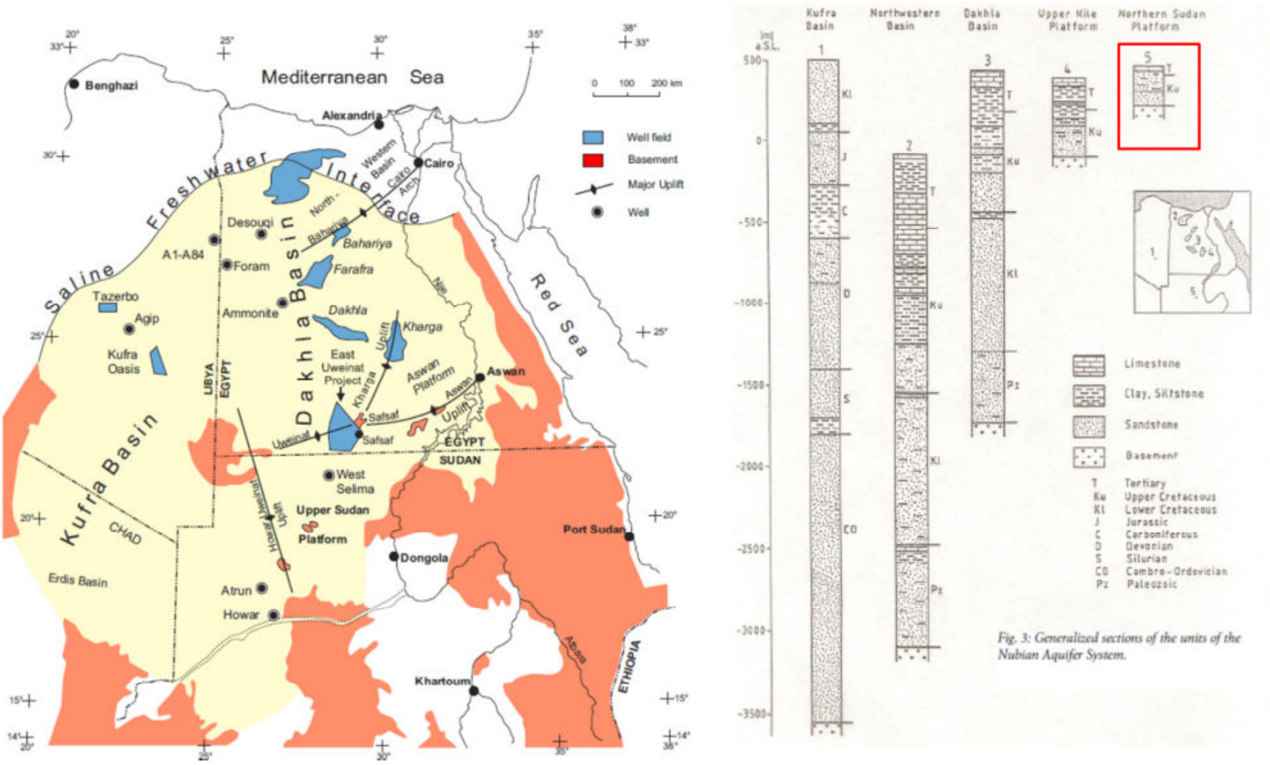

Figure 5: Let panel the Nubian Aquifer System. To the right the geology in survey area shown with red.

The survey and interpretation

A SkyTEM312FAST with a dual-moment waveform, 500,000 NIA, and an acquisition speed of up 150 km/h was employed. This system was selected because of the economics provided by fast flying capability as well as its ability to deliver high near surface resolution and a great depth of investigation.

The TEM data was inverted using 1-D laterally constrained multi-layer models. On the basis of the lithological information, the TEM inversion results were interpreted as shown in figure 6.

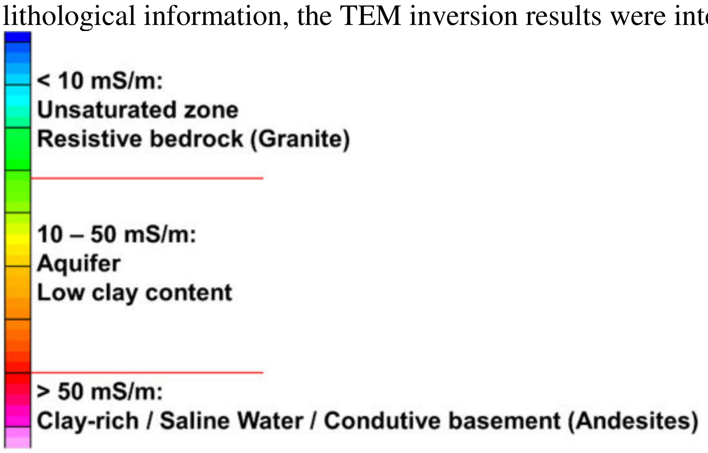

Figure 6: Interpretation of the different electrical conductivity levels

Based on the electrical conductivities, it was possible to delineate aquifer materials with low clay content. Figure 7 shows an example of the good correlation between a borehole and the conductivity intervals.

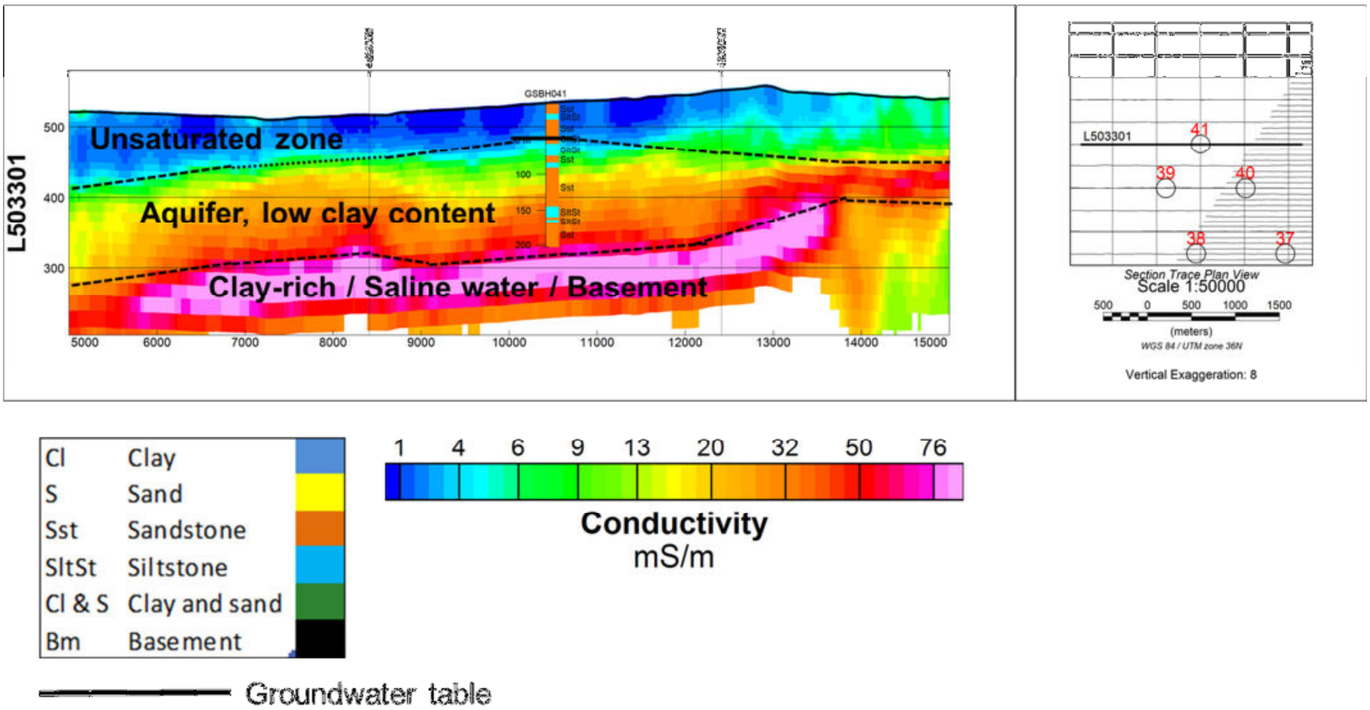

Figure 7: Correlation between a borehole and the electrical conductivities resulting from the 1-D inversions. The location of the groundwater table in the borehole is shown with a solid black line.

Interpretation of the electrical conductivities was employed to estimate the bottom of aquifers with low clay content as shown in figure 8. This surface ("aquifer bottom") was picked where the conductivity changes from below to above 50 mS/m.

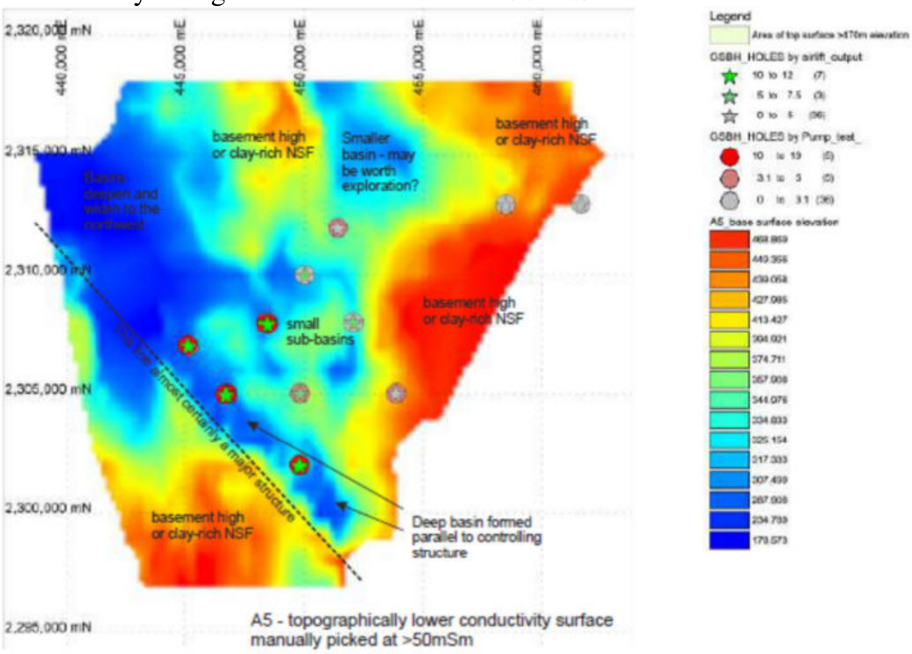

Figure 8: Map of lower conductivity surface picked at more than 50 mS/m

The map of the aquifer bottom shows several depressions in the surface. A number of boreholes were drilled in some of those surface lows while others were placed in surface highs. Airlift during the drillings as well as subsequent pump tests exhibited a positive correlation between low lying aquifer bottom and high borehole yield.

In conclusion, the TEM data provided valuable information for selecting drill targets. Furthermore, the combination of TEM and pump tests provided pivotal information on where to find favourable locations for real extraction wells.

AEM has greatly improved the ability to represent the actual hydrogeologic framework in groundwater models to an extent that is not achievable using traditional methods. Data collected with airborne electromagnetic surveys provide a method to characterize large and/ or remote areas quicker than traditional methods, and, when combined with data inversion and statistical analysis, can add to confidence in making earth management decisions. A dual-moment AEM system, along with carefully applied EM inversion modelling, is capable of providing both near-surface resolution (aggregates, engineering materials), as well as the ability to map targets at depth (sand channels, clay caps) and does a good job of discriminating lateral resistivity contrasts and layering. Water management over the coming decades will be based on the highly accurate groundwater flow models created by these datasets.

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References
Wijns, C. (2016), 'Airborne EM for mine infrastructure planning', Exploration Geophysics, 279-84.